⋄ Monograph Excerpt ⋄

Matter Antimatter Fluctuations

search, discovery and analysis of Bs flavor oscillations

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Preamble

To discover what the universe is made of and how it works, probing the deepest structure of space-time, is the challenge of particle physics. It is the aim to understand the elementary constituents of matter and their interactions. Such constituents, whose dynamics is governed by quantum mechanics along with special relativity, are referred to as elementary particles. Theoretical models are developed to describe the particles and their interactions, which are based on and, according to the principles of modern science, ought to be confronted with experiment.

To each particle corresponds an antiparticle counterpart which is its mirror-image: the pair carries the same mass but opposite charges. The phenomenon we set out to study involves rapid-fire transitions between matter and antimatter. These offer a highly sensitive probe of the particle interactions and models thereof. Their study may further contribute to elucidate one of the greatest mysteries in the universe, pertaining to the realm of particle physics and cosmology: the asymmetry between matter and antimatter and the apparent predominance of the former in the observable universe.

From signals in intricate detector systems to grand theories

Most elementary particles do not exist under normal circumstances in nature, but can be created and detected during energetic collisions of other particles. This is achieved in the laboratory with particle accelerators and detectors. The higher the energy of the collision, the deeper the structure of matter can be probed. The Tevatron collider at Fermilab accelerates protons and their antimatter, antiprotons, in an underground ring of 1 kilometer radius and smashes them head-on to produce the world's highest energy collisions obtained in the laboratory.

The remnants of such collisions are recorded as they traverse the material of detector systems surrounding the collision point. The traces of their passage, registered in the form of electronic signals, are used to reconstruct the particles' trajectories and ultimately infer their properties and interactions. The CDF detector, employed in the measurements we set forth, is an apparatus of about 12 meters in all three dimensions. It is striking that for studying the smallest objects in nature the largest research apparatuses are required. CDF has been built and operated by an international collaboration of about 700 physicists.

General purpose scientific apparatuses such as the CDF detector have a broad physics program aimed at scrutinizing the existing theoretical models and searching for exotic, unexpected phenomena. Despite the remarkable success of the current standard theoretical formulation, describing particles and their interactions, in accounting for the experimentally observed phenomena, it is believed to be an incomplete description of nature and that a more fundamental theory awaits discovery. The overarching goal, which is pursued in several distinct ways, is to find and understand what physics may lie beyond. It is the beauty and sophistication of experiments, the mathematical elegance and intricacy of theoretical conjectures, and all that lies in between that makes particle physics a most exciting human endeavor.

The fluctuating identity of neutral B mesons

B mesons are particles with very interesting properties. They are unstable, decaying to more stable, lighter products shortly after being produced in a collision. Nevertheless, they still live for a relatively long time, compared to other decaying subatomic particles, about 1.5 ps, flying a few millimeters in the center of the detector before decaying. One can then hope that they do something interesting while they are *alive*. Indeed, the neutral B mesons have the *sui generis* property of undergoing spontaneous transitions to their antiparticles, and back again. These transitions between matter and antimatter are extremely rapid. This is especially true for the B_s (pronounced "B sub s") mesons, for which such *flavor oscillations* are expected to occur at a rate of several trillion times per second. As it can be expected, it is extremely difficult to measure oscillations this rapid, and their observation has in fact evaded the many experimental attempts performed in the past, most prominently in the last two decades.

The relevance of the study of B_s flavor oscillations goes well beyond the determination of a peculiar property of this meson system. The measurement is used to constrain fundamental parameters of the underlying flavor model. It can constitute a probe for new physics and shed light on the mechanisms responsible for the observed matter–antimatter asymmetry in the universe. It is a major flagship measurement of the Tevatron physics program and arguably the most complex analysis ever attempted at a hadron collider.

The analyses

The search for and the study of B_s flavor oscillations constitute the objective of the analyses we set out to develop. After having collected large datasets of B_s mesons, their properties need to be extracted. The mesons' flight distance in the detector needs to be precisely measured, within tens of micrometers. Their momenta must also be determined from its decay products as accurately as possible. These quantities provide a determination of the time between production and decay of the B_s meson, in its own rest frame. Finally, one must determine its flavor, *i.e.* whether it was in a particle or antiparticle state, both when it decayed and at the time it was produced. The latter task is achieved with techniques named *flavor tagging*. Oscillations are searched for as time dependent flavor asymmetries in the data samples. In order to pin down the oscillation frequency most precisely, a sophisticated, multi-variate mathematical fit of the data is developed and performed. The samples and all the developed tools and techniques must be thoroughly understood and calibrated. This leads to the use of yet additional data samples, containing higher yields of lighter B meson species, namely B^0 and B^+, for method validation and tool calibration, which adds further to the complexity of the procedure.

The roadmap

This monograph is organized as follows. The analysis strategy is summarized in Chapter 1 and an overview of the theoretical foundations of neutral meson mixing is presented in Chapter 2. Chapter 3 gives a brief description of the accelerator complex and of the detector apparatus. The latter is employed to collect the data samples used in the analyses, which themselves are presented and characterized in Chapter 4. In Chapter 5 the fitting framework is first introduced, and likelihood techniques developed for befittingly describing the data samples at hand, leading to the measurement of the B mesons' lifetimes. The flavor tagging methods are introduced in Chapter 6, while a novel algorithm is further developed in Chapter 9. The flavor tagging information is incorporated into the likelihood description and applied to samples of the lighter B species in Chapter 7. As a result, a measurement of the oscillation frequency in the B^0 system is accomplished therein, along with a simultaneous calibration of the tagging techniques themselves. The calibrated flavor tagging algorithms are finally applied to the samples of B_s mesons in Chapter 8, where a first search for their rapid oscillations is carried out employing a suitable frequency scanning method. The precise measurement of the B_s oscillation frequency is achieved in Chapter 10, after extending the analysis on the full accumulated dataset, applying the flavor-tagger developed in Chapter 9, and further optimizations. The significance of the oscillation signal is estimated in Chapter 11. The obtained results are combined with other existing measurements and theoretical input in Chapter 12 for constraining the flavor model parameters. A layout of the analyses and the structure of the monograph are depicted below in Figure 2.

The discovery

The search for the particle-antiparticle oscillation is carried out via a sophisticated frequency scan of the data. The outcome of the analysis is represented in Figure 1. The results are shown in the form of a so-called amplitude scan, where possible oscillation frequencies have an amplitude consistent with unity whereas those not present in the data have an amplitude consistent with zero. The oscillating signal is found at 2.8 trillion times per second,

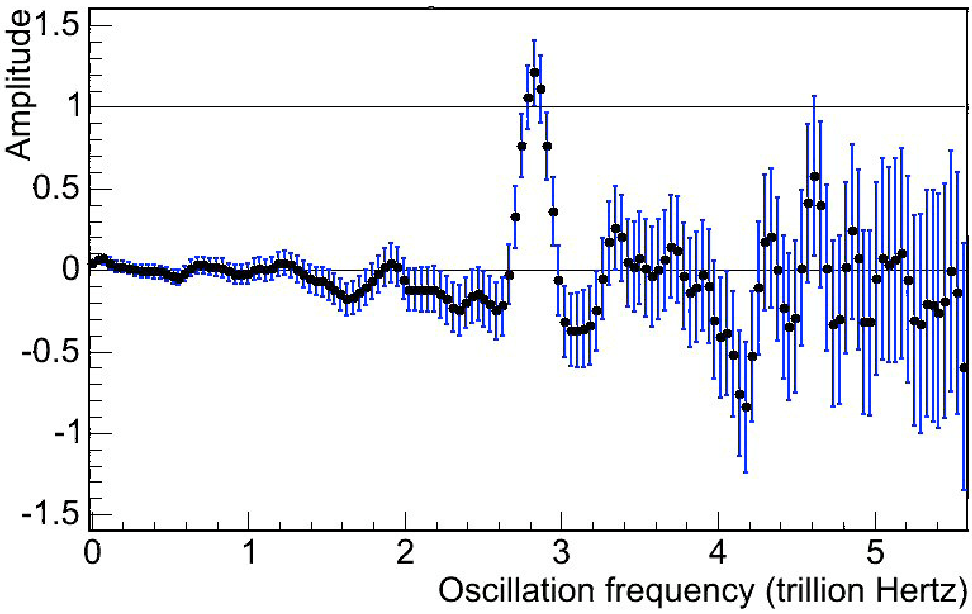

Figure 1: The outcome of the oscillation scan by CDF.

making it one of the highest rapid-fire phenomena occuring in nature. The probability of random fluctuations mimicking the signal is tiny, and the measurement exceeds the standard threshold criteria imposed for being qualified as discovery. The sub-percent precision of the measurement is also noteworthy. By yielding the world's first observation of B_s oscillations, the CDF analysis marks a final chapter in a long-sought goal within the field of experimental high energy physics.

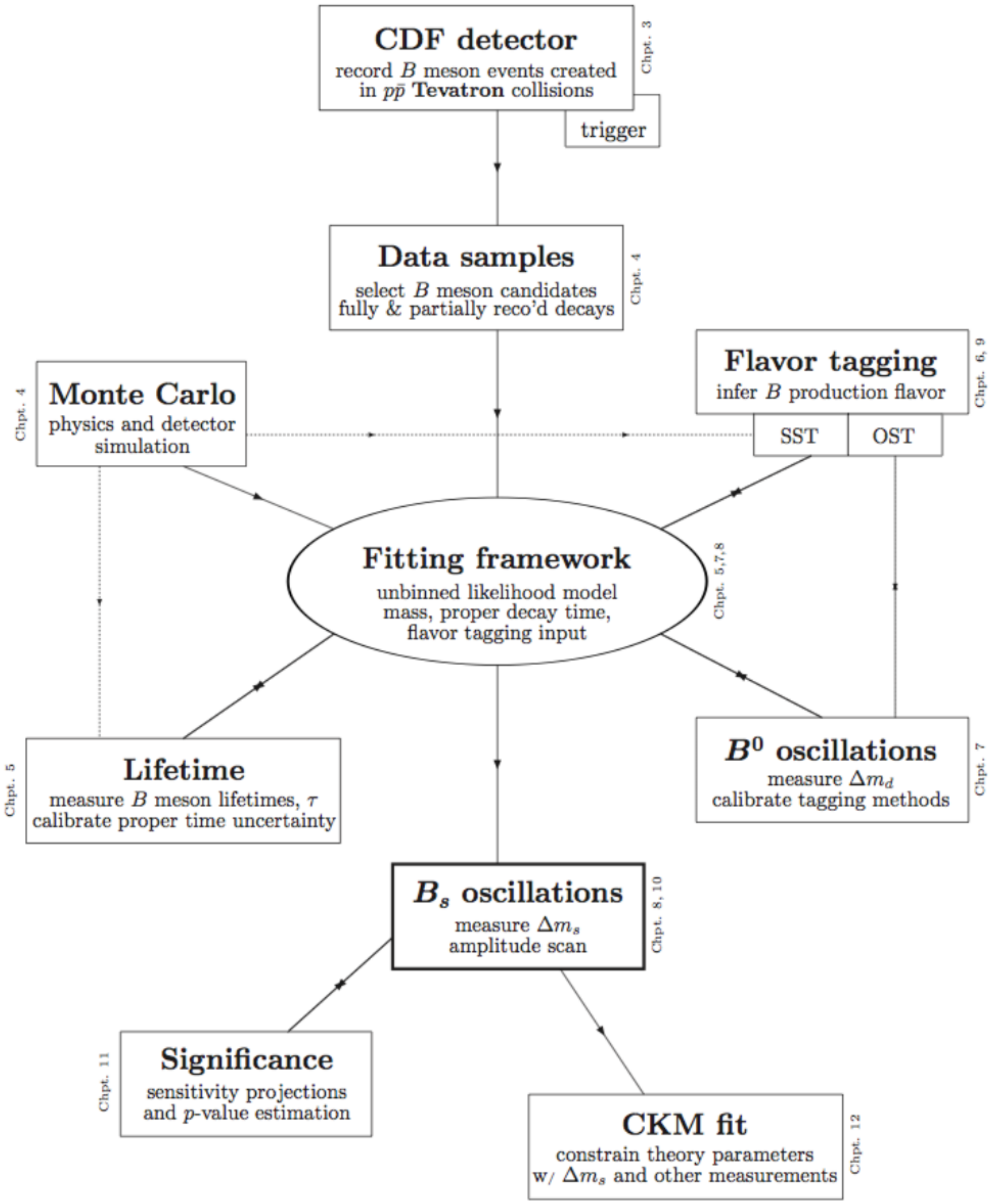

Figure 2: The big picture — analysis layout.